

Wind turbine noise: annoyance and alternative exposure indicators

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Summary

Ecological awareness increases energy production by wind turbines, but the considerable associated annoyance risk requires carefully designed noise control strategies when they are to be installed in densely populated regions. Well-chosen operational restrictions may reduce noise annoyance while preserving cost-effectiveness. This research project investigates the relationship between the inhabitants' wind turbine noise annoyance, exposure indicators, operational characteristics and environmental variables for a specific industrial site near a residential area. In contrast to most other research on wind turbine noise annoyance, in this study a six-month field experiment is conducted including regular on-line annoyance reports, continuous 1/3-octave band noise level registrations, periodic sound recordings, electricity production per minute and meteorological observations. Logistic regression reveals that the risk of high annoyance not only depends on the rotational speed, but also on the wind turbines' nacelle position relative to the location of the dwellings, i.e. the wind direction. This directivity effect can be captured when noise parameters such as the background noise level caused by other sources and a so-called fluctuation-indicator are introduced. Background noise measurements incorporate wind induced vegetation and road traffic noise; their L_{A95} -level is inversely related to the risk of high annoyance. The fluctuation-indicator is calculated from the 1/3-octave band spectra to capture the periodic part of wind turbine noise; here the risk of high annoyance increases with increasing fluctuation strength. These detailed findings can be used for designing operational restrictions that limit noise annoyance while keeping production as high as possible.

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1. Introduction

Ecological awareness has increased energy production by wind turbines [1, 2], but the installations might have adverse effects on their surroundings. Since their noise levels are most prominent in the closer vicinity of the turbines [2], it becomes especially important when turbines are erected in densely populated areas. Here, possible operational restrictions should balance neighbours' well-being and economical cost-effectiveness. Such restrictions can only be established if the noise characteristics most responsible for noise annoyance are identified. The finding that wind turbine noise annoyance occurs to a higher degree compared to other sources of community noise [3, 4, 5, 6] suggests that beside the A-weighted equivalent sound pressure level (L_{Aeq}) other factors should be taken into account [7, 8].

In this regard, background noise from other noise sources might affect noise annoyance. Although complete energetic masking is difficult to obtain [6, 9], environmental noise might still provide for informational masking of

the wind turbine sound [9]. Additionally, directivity and fluctuating character of wind turbine noise might as well be important. According to [10] directivity and fluctuation strength combine at the ground level to a non-trivial dependence of immission on direction. These fluctuations are approximately 2 to 3 dB, but can quite easily be detected by the human listener at levels of 1 to 2 dB below the background noise [11].

The main issue here is to quantify these phenomena and relate them to noise annoyance, since no relationship is found between varying annoyance response and psychoacoustic parameters like sharpness, loudness, roughness, fluctuation strength or modulation [7]. Furthermore, increasingly knowledge on exposure-effect relationships might be applied to establish intelligent operational restrictions, but this again requires parameters measurable in practice.

This research project investigates the relationship between wind turbine noise annoyance and exposure indicators, operational characteristics and context variables. Alternative noise immission indicators other than L_{Aeq} and the classical psychoacoustic parameters are linked to annoyance and to operational and meteorological data. If the latter is successful, on the one hand it proves the very tight relationship between the noise immission measurements

and the wind turbine noise emission. On the other hand, operational and meteorological information can then be used to steer the wind turbine rather than noise immission measurements that are more difficult to organize.

2. Material and method

2.1. Description of test site and wind turbines

Test site This study's test site (see Figure 1) is located in an urbanized area in the Flemish part of Belgium. The landscape is mainly flat with one two-by-two-lane road and several smaller roads closeby, a factory site and a residential area with all free-standing houses. Three wind turbines have been erected between the industrial buildings and the housing, the closest at about 270 m from the first houses.

Wind turbines The wind turbines have a rotor diameter of 82 m and a hub height of 90 m above the ground. The upwind rotor with active pitch control has 3 blades and rotates at 6 to 19.5 rotations per minute, the rated power is 2 MW.

Following previous complaints from the neighbors, two operational regimes are mostly used: unrestricted operation during the day (7h–19h) and restricted to 600 kW (or approximately 12 rotations per minute) at night (19h–7h). In addition, the closest turbine is stopped when cast shadows of moving blades causes flickering light inside the houses.

2.2. Noise measurements

Measurement setup The aim of the measurements is to find noise indicators that capture as closely as possible the experienced annoyance. Limited results of previous measurement campaigns in the area suggest that indicators beyond A-weighted sound pressure levels should be sought. The main aim of the current setup is obtaining a detailed noise assessment through long-term continuous sound registration. Therefore, practical constraints made it impossible to comply with IEC 61400-11 regulation [12] for the acoustic assessment of wind turbine generator systems.

Measurements are performed in the backyard of one of the houses closest to the turbines, meaning that there are no buildings between the closest turbine and the two different measurement points. The first microphone (from the 24th of February until the 26th of April) is set at 4 m height and at 1 m of the corner of a garage. The measurement point is close to some trees and other evergreen plants, hence a lot of wind induced vegetation noise is present at relative low wind speeds at ground level.

The second point (from the 7th of April until the 15th of August) is chosen near the north side of the house, 1.40 m high and 1 m from the façade. The microphone is shielded from the wind and some of the background noise by the house and a wooden frame at the backside of the garden.

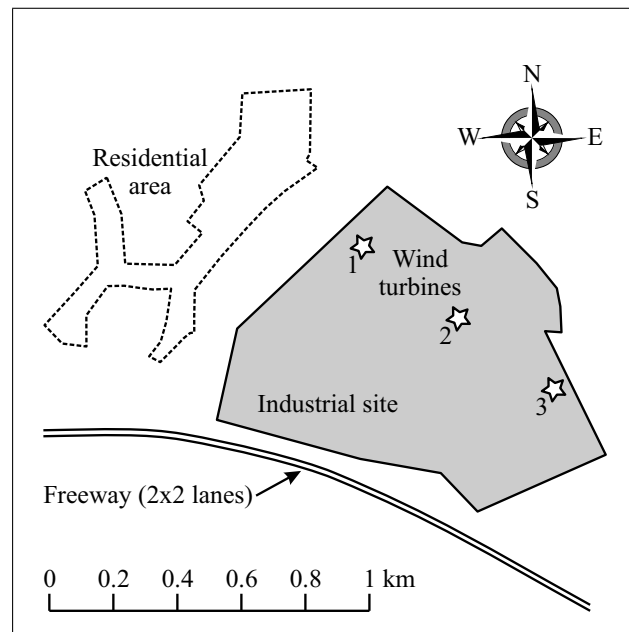


Figure 1. Schematic overview of the test site with the residential area and the major sources of background noise: the two-by-two lane road, the factory and the three windturbines.

Measurement equipment The measurement equipment is a Sinus Messtechnik Swing 4-channel measurement system using the SAMURAI 1.7 software. The basic goal is to measure continuous $\frac{1}{3}$ -octave band levels at subsecond timesteps ($\frac{1}{8}$ seconds) and record sound for 1 minute every 15 minutes. The setup is calibrated with a Svanetek calibrator (1kHz, 94 dB).

2.3. Operational and meteorological parameters

The operational parameters of the wind turbine closest to the dwellings are made available by the wind turbine operator, in particular angular blade velocity and the electric power production. In addition, the wind speed at hub height and the nacelle position—from which the wind direction can be derived—are provided.

Meteorological data, i.e. temperature and relative humidity, are retrieved from a permanent weather station, located several kilometers from the actual test site.

2.4. Annoyance assessment

An on-line web application (in Dutch) is set up so that the neighbors could report their annoyance from the 10th of March until the 20th of June by simply answering the question ‘How severely are you annoyed by the noise of the wind turbines at this moment?’ with ‘not at all’, ‘a little’, ‘rather/moderately’, ‘seriously/highly’ or ‘extremely’. Through a door-to-door campaign in the area, eight families willing to participate were found.

The webapplication enables a direct link between noise annoyance reports and long-term daytime annoyance, operational and meteorological data.

3. Results

3.1. Noise measurements

3.1.1. Additional emission by wind turbines

The overall noise level is assessed through measurements by the second microphone closest to the house to exclude wind induced vegetation sounds. To calculate percentile noise levels, data are aggregated first to a 5 seconds L_{Aeq} because $\frac{1}{8}$ second time averaged L_{Aeq} would possibly remove short blade passing events. In addition, a 10-minute time frame is chosen for evaluation because background noise, production and meteorological conditions can fluctuate quickly over time.

Extracting the contribution of the wind turbine from the overall noise level is a tedious task since operation of the wind turbine is strongly correlated with wind speed (at hub height) and so is background noise. Moreover, the sonic environment at the measurement location shows a clear diurnal pattern determined largely by the presence of industry and a two-by-two-lane road. In order to account for diurnal patterns, the contribution of the wind turbine to overall noise levels is extracted from differences in measured levels at the shielded point when the regime of the wind turbine changes: (1) during a forced stand still due to for example avoidance of shadow forming; (2) when the production limit is applied (19h00) or released (7h00). On the 10-minutes aggregated noise levels and production data gathered over test period, several inclusion criteria are applied to avoid unstable noise levels caused by the actual acceleration/deceleration or changes in wind speed; this results in (1) 107 useful observations during forced stand still and (2) 105 observations for production limits.

For the forced stand still (1), Figure 2 shows noise levels attributable solely to the closest wind turbine as a function of wind turbine rotations per minute, similar results are found for the production limits (2). The sound pressure levels thus obtained are slightly higher than theoretical predictions based on constructor sound power data and theoretical propagation models, namely 43.1 dB(A) at 18 rotations per minute and 40.3 dB(A) at 14 rotations per minute.

3.1.2. Background noise level

As already mentioned in the introduction, background noise such as wind induced vegetation sounds or road traffic noise might provide for informational masking of the sound from the turbines [9]. From the unshielded measurement point percentile levels L_{A95} are selected for observations where the blade angular velocity is lower than 10—to avoid contribution of the wind turbine—and L_{A95} is lower than 60 dB(A)—to omit unrealistic high values.

On this particular site, the major background noise sources are expected to be vegetation, the two-by-two-lane road and the factory. Multiple linear regression analysis ($\alpha = 0.05$) confirms that background noise increases with increasing wind speed, levels are especially elevated during morning rush hour and peaks are observed on Tuesday's and Friday's whereas the background drops during

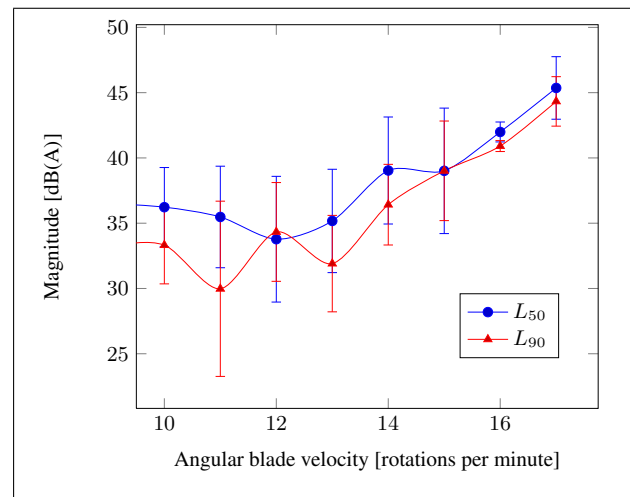


Figure 2. Contribution of the closest wind turbine to the sound pressure level measured at the second microphone closest to the house. Estimations and interval errors are made from forced stand still and plotted as a function of angular blade velocity.

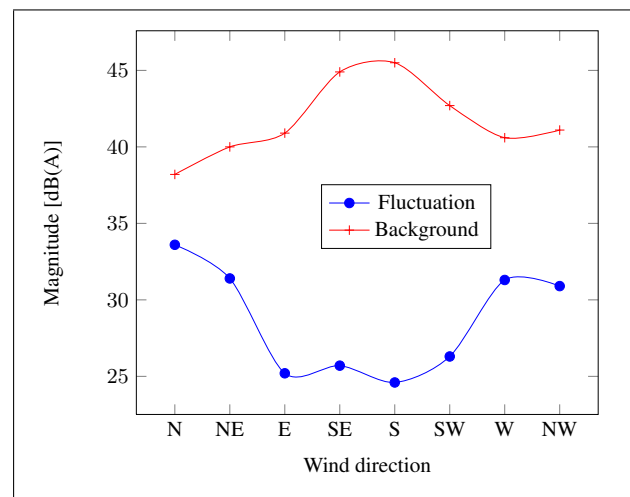


Figure 3. Median fluctuation-indicator and mean background noise level per wind direction.

weekends. For the wind direction, the average background levels are depicted in Figure 3. Southern and Southeastern wind raises the background most whereas Northern wind is associated with lower levels.

Since the established statistical model yields a quite satisfying adjusted R^2 of 0.73, it is used to predict the background levels included later on in Section 3.3.1.

3.1.3. Periodic noise part

To find a measurable parameter for quantifying the periodic or fluctuating character of wind turbine noise, the power spectrum of the $\frac{1}{3}$ -octave band $\frac{1}{8}$ -seconds time series is taken after removing the mean amplitude. The time interval for obtaining this spectrum is set to one minute which is short enough to not average out the periodic part in background noise and long enough to actually capture the fluctuations. Additionally, many disturbing sounds such as a car or plane passage take less than one minute

and can thus be removed by the spectral analysis. To further summarize the many thousands of minutes of sound level data, the spectral level at the frequency corresponding to the instantaneous angular velocity of the blades is selected, yielding a so-called ‘fluctuation-indicator’.

Oerlemans [10] has shown that the fluctuating character of wind turbine noise is closely related to directivity. Based on his work, the highest fluctuation strength at the microphones’ location is theoretically expected for North–North-East (-3° to 33°) wind and to a lesser extent for North–West–West (267° to 303°) wind. Plotting the median fluctuation-indicator per wind direction partly confirms this theoretical prediction. Only observations during times when the blade angular velocity reached at least 10 rotations per minute are taken into account to avoid artifacts when the wind turbine rotates too slowly to actually cause noise.

3.2. Annoyance reports

3.2.1. Annoyance and overall noise level

Three of the eight participating families actually reported regularly, yielding 552 reports in total. The response rate shows no clear changes over the four-months test time, nor are there clear week-weekend or day-evening patterns.

A one-way ANOVA is used to assess the relationship between annoyance and overall noise levels (L_{A50}) measured by the second microphone closest to the house. Figure 4 illustrates that higher levels of annoyance indeed correspond to higher noise levels measured by the second microphone which is somewhat shielded from wind induced vegetation noise ($p < 0.001$). For the first microphone closer to the trees, no statistical significant relationship could be found ($p > 0.05$), suggesting that this noise level is dominated by other sources of background noise than the wind turbines.

It is not surprising that the reported annoyance is proportional to the noise levels, but this analysis allows to put the current result in a broader perspective by comparing it to larger scale research—no luxury taking into account the limited number of respondents. The effect threshold in the current study is situated slightly above 30 dB(A) which is also the threshold found in epidemiological studies with more than a thousand people [3]. Also the increase with sound pressure level shows the same trend in the current study and the large-scale studies. This shows that longitudinal reports by a small group of people even during changing operational conditions establish the same trends as cross-sectional reports by large groups of subjects on different wind turbines at different distances and operational conditions.

3.3. Modeling noise annoyance

As stated in the introduction, the current research aim is not to model exposure-response relationships as such, but rather to quantify noise characteristics closely related to annoyance and select those parameters that could actually be used to steer wind turbine operation in practice.

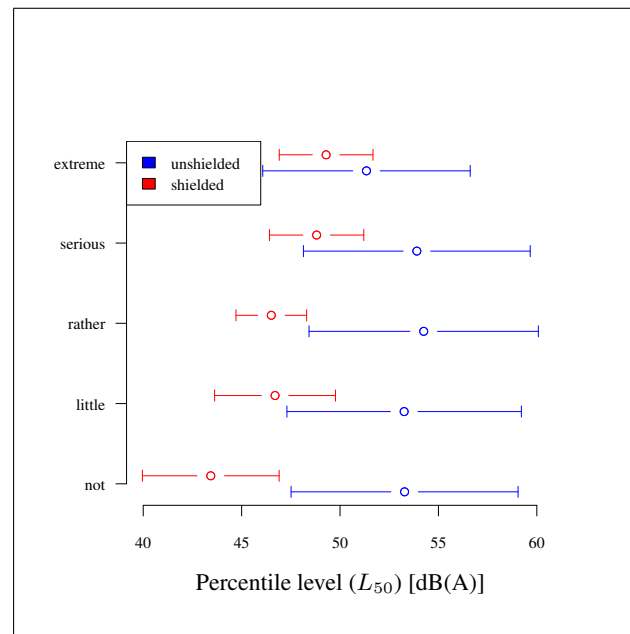


Figure 4. Reported annoyance and mean L_{50} (plus or minus one standard deviation). Shielded refers to the second microphone closest to the house and unshielded to the first closer to the trees.

To comply with the latter condition, manual step-forward logistic regression is first carried out for risk of high annoyance (serious or extreme reports) with operational and meteorological parameters as candidate independent variables. This yields to a model where blade angular velocity ω ($p < 0.0001$), wind direction Q (North, North-East, East, South-East, South, South-West, West, North-West) ($p < 0.0001$) and the relative humidity ρ (in %) ($p < 0.01$) are shown to be statistical significant

$$P(\text{HA}) = \frac{1}{1 + \exp(-X\beta)} \quad (1)$$

$$X\hat{\beta} = -7.44 + 0.602 \cdot \omega + \mathbf{Q} \cdot \boldsymbol{\delta} - 0.0232 \cdot \rho \quad (2)$$

with

$$\mathbf{Q} = [+0.103, -0.137, +0.000, -0.463, -1.569, -0.809, -0.768, -0.702],$$

$$\boldsymbol{\delta} = [\{N\}, \{NE\}, \{E\}, \{SE\}, \{S\}, \{SW\}, \{W\}, \{NW\}]^T$$

and

$$\{c\} = 1 \text{ if subject is in group } c, 0 \text{ otherwise.}$$

For the blade angular velocity (Figure 5), it is evident that noise emission will increase as the wind turbine rotates faster. The finding that risk of high annoyance decreases with humidity might suggest that people are more likely to go outside or open windows during dry weather, thus increasing noise exposure and possible annoyance. Finally, Figure 6 shows that the probability for high annoyance is highest for Northern wind and lowest for Southern

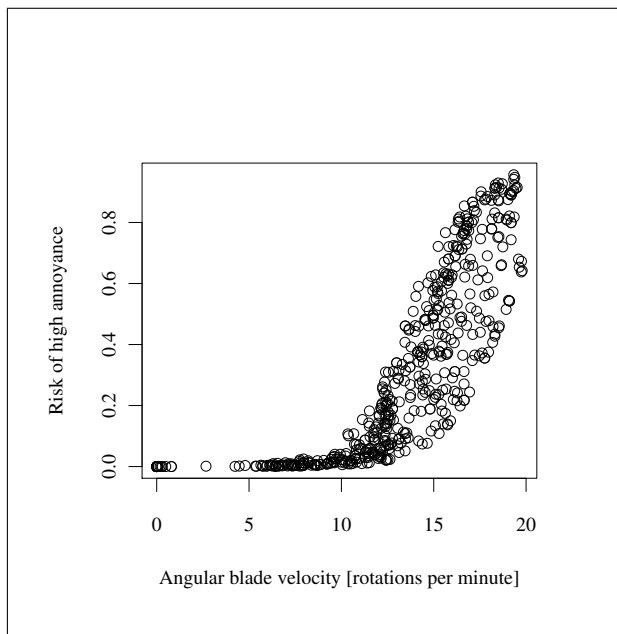


Figure 5. Risk of high annoyance as a function of angular blade velocity, taking into account wind direction and relative humidity.

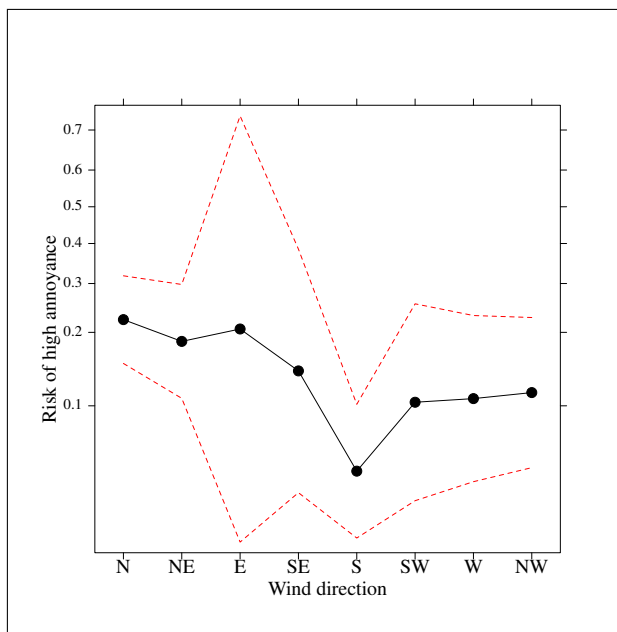


Figure 6. Risk of high annoyance as a function of wind direction. The black dots represent the fitted probability at each level of the categorical predictor, the red lines are the lower and upper bound of a 95 % confidence interval.

wind. (Eastern wind should not be taken into account due to lack of data.)

Although this model is very useful to steer the wind turbines in this particular site, it does not provide further insight in the underlying mechanisms of noise annoyance, i.e. in noise characteristics related to annoyance. Hence further analysis are carried out.

In section 3.1.2 and 3.1.3 it was shown that background noise levels and the periodic part of the noise are related to the wind direction. Furthermore, these noise parameters might also influence the perceived annoyance; more pronounced fluctuations increase perception and possibly annoyance whereas higher background levels might have the opposite effect.

It is verified with logistic regression whether these assumed effects can be formalized by replacing the variable wind direction in the previous model (Equation 2) by the predicted background levels \widehat{L}_{A95} (dB(A)) (Section 3.1.2) and the median fluctuation-indicator ϕ (dB(A)) (Section 3.1.3). This yields for the general Equation 1 to

$$X\hat{\beta} = -8.75 + 0.625 \cdot \omega + 0.117 \cdot \phi - 0.0684 \cdot \widehat{L}_{A95} - 0.0225 \cdot \rho \quad (3)$$

with all independent variables having a statistical significant influence ($\alpha = 0.05$) and coefficients consistent with the expected effects.

The goodness-of-fit remains convincing and typical measures for the model's predictive power [13] are almost as good for the new model as compared to the previous one (Equation 2). This suggests that combination of background level and fluctuation-indicator codes for almost all site specific annoyance-effects captured by the variable wind direction. The separate influence of those two noise parameters is difficult to entangle because they appear quite strongly inversely correlated (Spearman $\rho = -0.45$; $p < 0.0001$).

4. Discussion

In this project, long-term recordings of acoustical and operational variables are combined with annoyance assessments, making this almost a laboratory experiment—with extensive knowledge of varying input parameters—in a home environment.

Nevertheless, the major limitation of this project is the limited number of active participants. Although they have reported annoyance consequently during the test period, their representativeness for the larger community might be questionable. The main issue here is whether the other neighbors are fundamentally not annoyed, or whether their choice not to participate is inspired by other factors.

Risk of noise annoyance is undoubtedly related to non-acoustical parameters depending on the subject, exposure contexts and other socio-economical factors. However, theoretical predictions of directivity and noise fluctuation suggest that the acoustical characteristics themselves might differ substantially from one location to another, making it feasible that in certain parts of the neighbourhood the perceived annoyance is (much) higher than in others. Moreover, the correspondence with larger-scale studies described in Section 3.2.1 supports the idea that the current findings are to a certain extent transferable.

The present research project aims to quantify acoustical features important for noise annoyance. The fluctuating character often mentioned in qualitative descriptions

of wind turbine noise has been objectified and appears to be related to an increase in the risk of high annoyance, whereas higher background noise lowers the risk of annoyance (see Section 3.3.1). For the latter parameter exists some ambiguity in literature; Hoen [14] could not establish masking effects of wind noise on subjective rating of wind turbine noise whereas Bolin *et al.* [9] state that natural background noise have positive effects on perceived loudness although the in-field effects are to be studied [15]. Here, the established regression model is unable to reveal possible causal relationships between annoyance, background level and fluctuation or even upon the strength of the parameters' individual influence since both noise measures are correlated and possibly coding for underlying factor(s).

Linking annoyance to objective parameters might be useful to steer the wind turbines so that annoyance can be reduced. Although there is some scepticism about the real effects of operational restrictions [14], nighttime bans are already considered good practice [3] and in the current neighborhood complaints mainly rise during (unrestricted) daytime since angular velocity of the blades is limited to about 12 rotations per minute between 19h and 7h. All this suggests that an extension of the restrictions period will decrease the annoyance further.

5. CONCLUSIONS

The current research based on long-term annoyance reports and noise measurements suggests that the risk of high annoyance depends not only on the angular velocity of the blades, but also on site-specific variables such as wind direction. The latter effect is probably (partially) attributable to the relationship between wind direction, wind turbine fluctuation noise and background noise from other sources.

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References

- [1] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. European Parliament and Council, Brussels 2009.
- [2] A. Van Rompaey, S. Schmitz, C. Kesteloot, K. Peeters, B. Moens, H. Van Hemelrijck, V. Vanderheyden, M. Loopmans, S. Broucke: Landscape capacity and social attitudes towards wind energy projects in Belgium (2010).
- [3] E. Pedersen, F. van den Berg, R. Bakker, J. Bouma: Response to noise from modern wind farms in The Netherlands. *The Journal of the Acoustical Society of America* **126** (2009) 634.
- [4] A. Salt, T. Hullar: Responses of the ear to low frequency sounds, infrasound and wind turbines. *Hearing research* (2010). ISSN 0378-5955.
- [5] E. Pedersen, P. Larsman: The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines. *Journal of Environmental Psychology* **28** (2008)(4) 379–389.
- [6] E. Pedersen, F. van den Berg, R. Bakker, J. Bouma: Can road traffic mask sound from wind turbines? Response to wind turbine sound at different levels of road traffic sound. *Energy Policy* (2010).
- [7] K. Persson, E. Öhrström: Psycho-acoustic characters of relevance for annoyance of wind turbine noise. *Journal of sound and vibration* **250** (2002)(1) 65–73.
- [8] E. Pedersen, K. Waye: Wind turbines–low level noise sources interfering with restoration? *Environmental Research Letters* **3** (2008) 015002.
- [9] K. Bolin, M. Nilsson, S. Khan: The potential of natural sounds to mask wind turbine noise. *Acta Acustica united with Acustica* **96** (2010)(1) 131–137.
- [10] S. Oerlemans: Detection of aeroacoustic sound sources on aircraft and wind turbines. Ph.D. thesis, University of Twente 2009.
- [11] E. Pedersen, H. Halmstad: Noise annoyance from wind turbines: A review (2006).
- [12] Wind turbine generator systems. Part II: Acoustic noise measurement techniques. *International Electrotechnical Commission* 2002.
- [13] F. Harrel: Regression modeling strategies: with application to linear models, logistic regression and survival analysis. Springer-Verlag, New York 2001.
- [14] B. Hoen: Assessing the Impacts of Reduced Noise Operations of Wind Turbines on Neighbor Annoyance: A Preliminary Analysis in Vinalhaven, Maine (2010).
- [15] E. Pedersen, F. van den Berg: Why is wind turbine noise poorly masked by road traffic noise? In: *Proceedings Inter-noise 2010*. SPA, SEA, Lisboa 2010.